Acquisition and Representation of Knowledge for Distributed Command Decision Aiding

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Final Report

December 1, 1987

Contract Number: N00039-87-C-5301

Work Unit Number: 686-001

Period Covered: July 15, 1984 to July 15, 1987

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ADA198957

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RMI-87-025	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Acquisition and Representation of Knowledge for Distributed Command Decision Aiding		5. TYPE OF REPORT & PERIOD COVERED Final Report 7/15/84 to 7/15/87
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Bruce W. Hamill and Robert L. Stewart		8. CONTRACT OR GRANT NUMBER(s) N00039-87-C-5301
9. PERFORMING ORGANIZATION NAME AND ADDRESS Johns Hopkins University Applied Physics Laboratory Laurel, MD 20707		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Work Unit 686-001
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Code 1142PS Arlington, VA 22217-5000		12. REPORT DATE December 1, 1987
		13. NUMBER OF PAGES 39
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release;
Distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

knowledge acquisition, knowledge representation, decision aiding, decision making, planning, cooperative planning, distributed tactical decision making

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research addressed the problem of distributed tactical decision making (DTDM), with the focus on Naval tactical mission planning by teams of peers responsible for mission operations in anti-air (AAW), anti-submarine (ASW), and anti-surface (ASUW) warfare. An interdisciplinary approach was employed, combining techniques from cognitive psychology, artificial intelligence, and computer science and focusing on the problem-solving — over

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20. Abstract (Cont.)

behavior of experienced human subjects in realistic tactical situations. Our contributions have been in the areas of (a) structuring this complex problem in such a way as to address its three primary dimensions (psychological, computational, and communicative) and their interrelationships in a composite theoretical framework, (b) approaching the fundamental issues involved in distributed decision-making performance by tactically experienced personnel through the use of realistic Naval tactical problems and structured interviews, (c) focusing on the planning process and its products as critical elements in individual and team problem-solving and decision-making performance, and (d) developing a computer-based experimental interview and simulation system to support the presentation of tactical problems and the acquisition and representation of subjects' plans and knowledge. (KR)

This research project attempted to address the problem of distributed tactical decision making (DTDM), that is, tactical coordination by Naval commanders who may be spatially, electronically, and organizationally separated from one another while they are performing problem-solving and decision-making tasks requiring substantial specialized domain knowledge, experience, and expertise. The underlying concept of the research was that it may eventually be possible to support decision-making peers, such as Naval warfare area commanders, by using local instantiations of a common knowledge-based decision-aiding system incorporating doctrine and expertise from the relevant mission areas. A prerequisite for the design of such systems is to determine the nature of knowledge structures and processes involved in the dynamics of decision making in the complex domain under investigation. Therefore, the focus of the research was narrowed to a critical aspect of Naval tactical decision making -- ongoing mission planning by teams of peers responsible for mission operations in the areas of anti-air (AAW), anti-submarine (ASW), and anti-surface (ASUW) warfare -- to permit a detailed examination of the knowledge and interaction processes involved in decisions about planning as they are made by experienced tactical decision makers faced with realistic problems in a complex tactical scenario: What do real people do in realistic situations, and what do they need to know to do it?

Given the goal of structural-symbolic explanatory modeling of human performance in an ongoing planning process, the research objective was to identify critical factors related to the acquisition, representation, and utilization of knowledge in a postulated knowledge-based decision support system for the domain in question, emphasizing requirements for distributed support of spatially separated decision makers. This entailed development of a descriptive methodology which would support (a) determining the nature of technical and general knowledge

brought to tactical problems by experienced decision makers, (b) identifying appropriate representational formalisms with which to model such knowledge in computer software in support of both a structured interview process to be used to elicit knowledge from decision makers and the skeleton of a decision support system which might eventually be based upon such knowledge, and (c) designing software to support the utilization of knowledge thus represented in the system in a canonical model of the team decision-making process, that is, a generalized structure that meets knowledge requirements of all peers in a distributed decision-making environment.

An interdisciplinary approach was employed, combining techniques from cognitive psychology, artificial intelligence, and computer science and focusing on the problem-solving and decision-making behavior of experienced human subjects in realistic tactical situations. The initial focus was on constructing a multidimensional taxonomic framework which would incorporate psychological requirements of multiple human decision makers, computational requirements related to the Naval command and control process, and communications requirements for support of distributed decision-making nodes. This framework is described in Hamill and Stewart (1986a) (see Project Reports below). This approach affords a direct look at the complexity of expert performance and at the knowledge required for that expert performance. Upon full development of models constructed within this framework, it could also permit qualitative and quantitative measurements of the performance of the distributed decision-making process model by comparing model-based simulation performance with the actual performance of teams of experienced subjects in tactical problem situations.

Our contributions have been in the areas of (a) structuring this complex problem in such a way as to address its three primary dimensions (psychologi-

cal, computational, and communicative) and their interrelationships in a composite theoretical framework, (b) approaching the fundamental issues involved in distributed decision-making performance by tactically experienced personnel through the use of realistic Naval tactical problems and structured interviews, (c) focusing on the planning process and its products as critical elements in individual and team problem-solving and decision-making performance, and (d) developing a computer-based experimental interview and simulation system to support the presentation of tactical problems and the acquisition and representation of subjects' plans and knowledge. The structures we used to capture subjects' knowledge concerning plans for tactical missions facilitated decomposition of the complexities of the problems we posed and of the responses of the subjects, and they permitted comparison of the relative importance of various factors in the distributed decision-making process among subjects, both as individuals and as teams, for specific aspects of the tactical problems posed.

Our empirical findings from the structured interview process contributed to the definition of sets of schemas for representing subjects' plans and planning processes, both for individuals and for teams of decision makers. Through the use of our analysis procedures, we decomposed planning, problem-solving, and decision-making tasks contained in realistic tactical problems into identifiable components and represented them in schema structures that capture essential aspects of those tasks. We produced generalizable schemas which directly address the requirements of such tasks by emulating the performance of experienced decision makers faced with tactical problems. We also addressed the necessity of representational formalisms to augment schemas, such as production rules and scripts, for specifying the planning elements and knowledge states entailed in distributed problem solving and decision making.

The following sections summarize our work on knowledge acquisition, representation and utilization; the experimental interview environment, including the use of agents; and planning in distributed decision making, including analyses of platform dispositions and team interview protocols, schema-based representations, and aspects of a process model of distributed planning and decision making.

Knowledge Acquisition

To identify and classify representation requirements, representative DTDM events were exercised in controlled interview settings. Since tactical knowledge is largely situational in nature, we posed structured tactical problems to our subjects in order to have a framework within which to elicit their expertise, and in order eventually to be able to make comparisons (across decision makers) among their responses in an organized quest for common structures in their decision processes. Existing tactical problems developed at JHU/APL from official Navy scenarios for the 1990s were used.

Coordinated with the use of such tactical problems was the use of a computer-based scenario generation, interview, and simulation system that we developed for acquiring and exercising knowledge from experienced tactical decision makers. The associated interview techniques were aimed at eliciting responses about what subjects were doing and thinking in the course of solving problems and making decisions, and at doing so in such a way as to be able to derive both explicit and implicit interpretations of the knowledge and processes being used to perform these tasks.

Knowledge Representation and Utilization

There are many possible ways to represent knowledge. Each approach is based on assumptions about the qualitative nature of the knowledge and mental processes to be represented. It is therefore necessary to determine the

nature of the knowledge that a system will be expected to use before decisions can be made about the system architecture and the best way to represent the knowledge within that architecture (see Hamill, 1984). Our research addressed this issue by analysis of knowledge structures obtained in the knowledge acquisition phase (above) and their relationship to the multidimensional taxonomic framework described earlier, and in terms of _a priori_ structures derived from relevant psychological literature on organization of memory for problem solving and decision making.

Candidate psychologically-based representation structures included semantic association networks, strict and "tangled" hierarchical taxonomic structures, contextual schemata or "frames," "script" representations, a skill-, rule-, and knowledge-based human performance framework, a "cognitive architecture" form of representation, production rule structures, procedural structures, and various hybrids comprising mixtures of these and other such structures. Many of these psychological models have current instantiations in computer software systems developed by psychologists and computer scientists in the course of their research. The availability of such systems can facilitate the conduct of laboratory and field experiments designed to examine the effects of alternative structural representations of knowledge on problem solving and decision making performance.

Central to our concept and purpose was the representation of the knowledge of multiple decision makers within the same decision aiding system framework. This entailed analyses aimed at determining which aspects were shared among decision makers and which were idiosyncratic. This dimension of decision making performance may be a significant factor in establishing a basis upon which to build a distributed command decision aiding system of the kind mentioned above. These analyses yielded identifiable qualitative components of the decision

processes involved, and some of those components were quantitatively measurable. These results are described below.

The use of knowledge represented throughout a distribution of tactical command nodes for DTDM can be partitioned into use of local and external knowledge elements. Under the assumption that optimal processing efficiency and accuracy will result when common knowledge structures and processes are used for both local and external knowledge elements (as in NTDS), we used common language structures and processes for acquisition, representation, and use of knowledge elements in our composite processing model and in our interview system.

Experimental Interview Environment

Interview system development. To model and test DTDM processes we developed a three-node computer-based interview and test system (see Stewart and Hamill, 1986). The nodes may be used to represent any triad of decision-making peers, but our research objectives focused on mission requirements defined for anti-air, anti-submarine, and anti-surface warfare area commanders (AAWC, ASWC, and ASUWC, respectively).

The environment consists of control programs operating on VAX 11/780 and SUN 3/75M computers and separate interactive mechanisms for experimenter or test subjects to specify initial problem conditions, knowledge representation, and decision-making processes. An initial form of the test environment incorporating a Navy battle group scenario, composite warfare commander (CWC) doctrine, and separate AAWC/ASWC rules of interaction represented in structures of the production system language known as OPS-5 was demonstrated in October 1984.

Major weaknesses observed in the OPS-5 knowledge representation in the initial test environment included an inability to support continuous event-

driven tactical conditions and the restriction to a single inference mechanism for all levels of abstraction. These observations were reflected in our taxonomic analyses and led to a second design effort.

Based on direct verification of the predicted ability of YAPS (Yet Another Production System -- developed at the University of Maryland) to support event-driven tactical scenario representations and multiple independent knowledge bases, a second testing environment was developed and used to orient the initial design of protocols for documenting subject interactions in simulated distributed tactical decision-making tests. (The OPS-5 environment was retained for possible benchmark trials.)

In the YAPS-based interview system we are able to interact with multiple decision makers to present scenario descriptions of varied validity (with separate ground truth), incorporate scenario changes specified by test subject or experimenter, exercise rule-based decision processes keyed to different levels of abstraction (including explanations), and modify rule-sets. Using the YAPS language and the MIT Flavors structures that are intrinsic to the University of Maryland Franz LISP environment, we can instantiate different knowledge bases as unique programming "objects" and thereby model distributed decision-making protocols more directly. We started development of selected protocols for timing and environmental monitoring functions associated with interrelated tactics among distributed peers.

The YAPS-based interview system was developed on a VAX 11/780 using UNIX version 4.1. We later acquired and installed the University of Maryland Franz LISP environment (including YAPS) modified for use with UNIX version 4.2 on a second VAX 11/780. The UNIX 4.2 environment is preferable because it provides stronger interprocess communications capabilities for distributed knowledge base interactions in our interview system environment.

Interviews of tactical decision makers. In coordination with other analysts at JHU/APL we identified relevant and validated tactical scenarios for support of our DTDM interview and test process. To achieve maximum benefit of analysis and display capabilities of JHU/APL wargaming facilities, we further refined the set of candidate DTDM scenarios to those also being used in the JHU/APL Warfare Analysis Laboratory (WAL). Using WAL scenarios that were also relevant to the DTDM project reduced the need for pre-test DTDM scenario analysis and extended the utility of WAL displays (e.g., hard-copy plots and listings) and analysis products to the DTDM project.

The scenario selected for DTDM interviews involved a USN task group (without a carrier) in wartime opposition to a Soviet task group in the Indian Ocean. This scenario had been used in the WAL to examine cruise missile engagements and was selected for the DTDM project because of the small number of units involved and the relative uniformity of mission requirements for the three areas of ASW, ASUW, and AAW. In addition, the special emphasis in the WAL on mission planning for this scenario was most opportune in that our principal interest in the DTDM effort was in planning processes and protocols for actuation of plans.

The analysis process began with each subject being presented the necessary information from the Officer in Tactical Command (OTC) for him to perform the duties of a warfare area commander (AAWC, ASWC, or ASUWC). With this information the subject was asked to prepare a plan for fulfillment of his responsibilities as a specified warfare area commander without concern for how the other warfare area commanders would want to allocate resouces. Planning elements developed by the subject were examined in concert with the experimenters to identify protocols for the planning, monitoring, and actuation functions.

Agent definition and testing. As part of the development of his plan, our first subjects were asked to define the agents they required to ensure

appropriate and timely observance of their plans. Agents so defined were referred to appropriate categories of our composite model and analyzed in terms of their psychological, computational, and communicative dimensions. For example, the functions that an AAWC might authorize a staff watch officer to perform in his absence or in time-critical situations might define an agent at the knowledge-based psychological level of our multidimensional taxonomic framework.

The next step was for the subject's plan and agents to be instantiated in the interview and test system in the form of displays, rule-sets, and algorithms as appropriate to the Human-Directed, Integrated Rule-Sets, or Automatic protocol levels of the framework (see Hamill and Stewart, 1986(a)). The agents defined by the subject were instantiated insofar as possible in unique object-oriented production systems, with the activation event for each agent incorporated within an overall control structure (see Gilbert and Stewart, 1986). For example, a low-level agent defined as the mechanism that ensures that incoming Flash messages are immediately brought to the commander can be defined as an independent rule-set that is activated every N seconds to examine incoming message traffic or is activated only on receipt of a Flash message.

Given the plan and agents specified by the subject, the subject's decision-making processes could then be stressed by exercising the plan and agents in controlled tactical scenarios that are representative of general tactical mission requirements. In order to focus our limited resources on issues most relevant to distributed decision processes, we constrained in-depth analysis of agent processes to the subset of agents clearly requiring interaction with agents at other nodes.

Some scenarios present opportunities for synergistic cooperation among different decision makers' agents with respect to mission area requirements, while others present them with conflicting mission requirements. Effectiveness of various agents under these several conditions can be observed and, where possible, measured against criteria derived from our taxonomic framework, including skill-, rule-, and knowledge-based processes in the psychological, computational, and communicative aspects of tactical decision making. Testing for conditions involving DTDM conflict or opportunities for synergy can be further accommodated by concurrent activation of all three nodes of the experimental environment, with decision-making processes being activated at each node by different subject-experimenter combinations or through use of agent rule-sets at one or more nodes.

While this approach to insight into the structure of the planning process through the definition of agents initially appeared promising, we found that subjects were inconsistent in defining agents as we had requested, with some subjects taking pains to honor our request and others disregarding it entirely. Since it turned out to be a burdensome requirement for some decision makers who preferred not to function at that explicit a level for our task, we discontinued further development of this approach. However, we still believe it to be a meritorious approach to defining steps in the transition from the initial planning phase to the execution and monitoring phases of the ongoing planning process, and that it deserves further research.

Planning in Distributed Decision Making

The purpose of our research on planning in distributed decision making (see Hamill and Stewart, 1985, 1986(b); Stewart and Hamill, 1987) was three-fold. First, we attempted to identify planning elements associated with effective

planning and coordination of decisions by peer-level decision makers in an open system environment. These elements include planning and decision protocols observed in controlled interactions of knowledgeable decision makers and components of the planning process that support coordinated decision making by spatially separated peers.

Second, we tried to identify knowledge requirements for those planning elements associated with distributed decision making. These include knowledge states that are reflected in decision-making protocols of experienced decision makers, data and communication requirements that are unique to interactions of agents (mechanisms to achieve desired outcomes or states) defined by experienced decision makers, and knowledge and its forms of representation needed by each decision-making peer for recognition of potential conflict and synergy with others' plans.

Third, we attempted to identify information flow and communication requirements that are unique to distributed decision making in terms of a process model and events that provide requirements or opportunities for coordinated planning or actions.

Theoretical considerations. We began our research by developing a taxonomy of information processing functions expected to be associated with distributed decision making in an open system of decision nodes. We identified three dimensions of the DTDM system: (1) psychological requirements, including skill-, rule-, and knowledge-based processes (Rasmussen, 1974, 1983, 1986; Rasmussen & Lind, 1982) of human decision makers at each node in a distributed system; (2) computational requirements for support of information processing in a complex system environment (e.g., Halushynsky & Beam, 1984; Lawson, 1984); and (3) communicative requirements to handle node-to-node communications functions supporting the planning and decision-making process, as in the International Standards

Organization's Open Systems Interconnection Model (Denning, 1985; Tanenbaum, 1981).

Within each of the three dimensions, the identification and placement of each functional category may be defended in terms of associated research and technology. Although organizations such as the U.S. Navy can be observed in distributed decision making that exercises similar functions, no support could be found for aligning any function horizontally in one dimension with another function in another dimension. Yet, it seems clear that unless such alignments are specified in detail, no comprehensive psychological, computational, and communicative process model can be developed for DTDM. Thus, our taxonomic description led us to a search for methods to refine functional definitions and to relate process levels within the composite structure.

In our search for ways to relate DTDM processes along the three dimensions posed, we placed special emphasis on the psychological and computational dimensions with the expectation that observations of human decision making and computer representations of associated knowledge would yield significant insights. As a specific problem domain to focus our study of psychological and computational elements of DTDM functions we chose planning.

Our theoretical work on the planning process underlying distributed problem solving and decision making is based on the model developed by Wilensky (1983). His formulation relates planning and understanding through the knowledge required for each: "...Planning includes assessing a situation, deciding what goals to pursue, creating plans to secure these goals, and executing plans....Understanding a situation involves inferring the goals, plans, and actions of the people in that situation, and relating these items to each other as well as to other aspects of the situation....What is common to planning and understanding is that both require recourse to essentially the

same sort of knowledge about plans" (p. 5).

This formulation provides a new theoretical view of distributed decision making which brings into play the role of expectations and the recognition of cues to others' intents and motives through observations of their actions. It also requires the use of an active plan shared by the decision makers and, lacking communication among them, modified by them individually on the basis of their respective interpretations of what is going on in the environment and, in particular, in response to what they perceive their peers to be doing. A major benefit of this approach is that it provides a means by which the several decision makers can coordinate their decisions and actions, even in complex situations and in the presence of restrictive environmental conditions, because it provides them a basis for understanding the intentions of the others as they execute and modify their parts of the shared plan.

Figure 1 depicts Wilensky's model of the ongoing planning/understanding process. Each decision maker interprets the current situation in terms of what he knows about priorities, available resources, nature of the problem, environmental conditions, and other factors. This interpretation process yields his momentary model of what is happening in the world, both as it affects him and as it affects his peers. On the basis of this world model he identifies current problems, detecting and stating his goals as they relate to solving those problems. Given his goal statements, he proposes plan elements to attain his goals. If these plan elements are deemed satisfactory, they are then added to his active plan; otherwise he projects the likely effects of the plan elements on the environment before selecting those which should be added to the active plan. Finally, the active plan is executed and the environment is monitored for effects of its activation, for new situations, for new problems, etc.

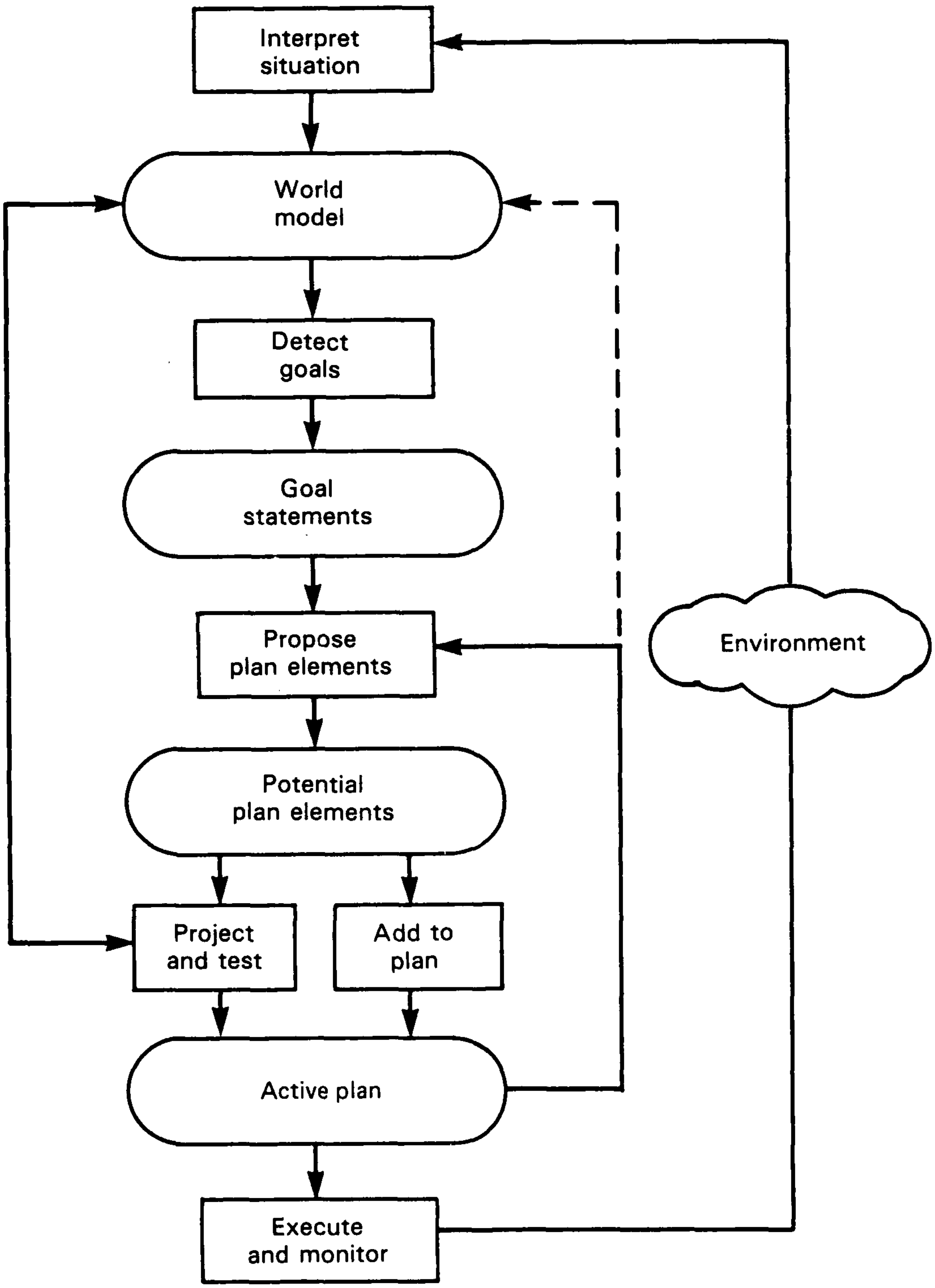

Figure 1. Ongoing planning process (after Wilensky, 1983).

An important aspect of the ongoing planning/understanding process in the distributed decision-making context is that it explicitly includes provision for coordinated replanning after activation of the initial plan. It can thus account for an evolving sequence of events as they occur in the environmental situation and for their interpretation and handling by multiple decision makers.

This formulation has implications for investigating and understanding distributed planning and decision making. First, it implies a process view for multiple nodes, with a single coherent plan comprising separate plans maintained at each node. Second, since there is a different decision maker at each node who has his own problems, his own goal sets, and his own world view, there is a need for compatible interacting knowledge states to support coordinated decision making. In addition, efficient interaction among peer nodes, rather than within a single node, entails appropriate representation and use of such knowledge. Third, in order for multiple peer-level decision makers to engage in coordinated planning and procedures within the same problem domain, it is essential that (1) objects of common interest be uniquely defined, (2) processes addressing those objects be procedurally and computationally compatible, and (3) communications among decision makers be adequate to support object and process referencing at appropriate levels of abstraction and efficiency. Our work led to some extensions of this model to support multiple decision makers. These extensions are described below.

<u>Interview and data collection procedures.</u> We designed and implemented an interview and analysis process involving manual and computer-based knowledge acquisition, representation, and simulation to support our analyses of actions and interactions of experienced tactical decision makers engaged in scenario-driven planning and coordination. This environment supports definition of

mission requirements at the top level of a hierarchical structure, planning requirements for three separate subordinate nodes, and presentation of tactical situations and problems. Figure 2 is a block diagram of the computer-based interview and analysis support system. Control of the system is exercised at the top level (by the experimenter) with mission specifications and the global data that reside in each subordinate node's knowledge base. Under ideal conditions, each node begins with the same global data. Each test subject, functioning at one of the subordinate nodes, is provided an ability to query and modify his local and global knowledge bases, and to define and activate planning, communications, and coordination activities.

Through control of the global data, the experimenter can specify scenarios and missions to provide the context in which subjects develop their plans. Analysis of these plans to identify decision protocols and agents is performed manually, followed by instantiation of those protocols and agents within the appropriate local knowledge base. Validation of these mechanisms can be achieved with the subject present through exercise of the computer-based form of his agents (if he defines any) against simulated tactical data provided under control of the experimenters.

Knowledge acquisition was conducted within a framework comprising the combination of warfare areas, event types, and coordination states. The three warfare areas (nodes of the distributed decision-making system), which are part of the Composite Warfare Commander (CWC) concept, are anti-air warfare (AAW), anti-submarine warfare (ASW), and anti-surface warfare (ASUW). The three event types, which were chosen to introduce realistic problems with specifiable structure, are changes in readiness of major assets or resources (such as weapon or sensor systems), unexpected changes in environmental conditions or threat characteristics, and abrupt changes in command structure; each such change is

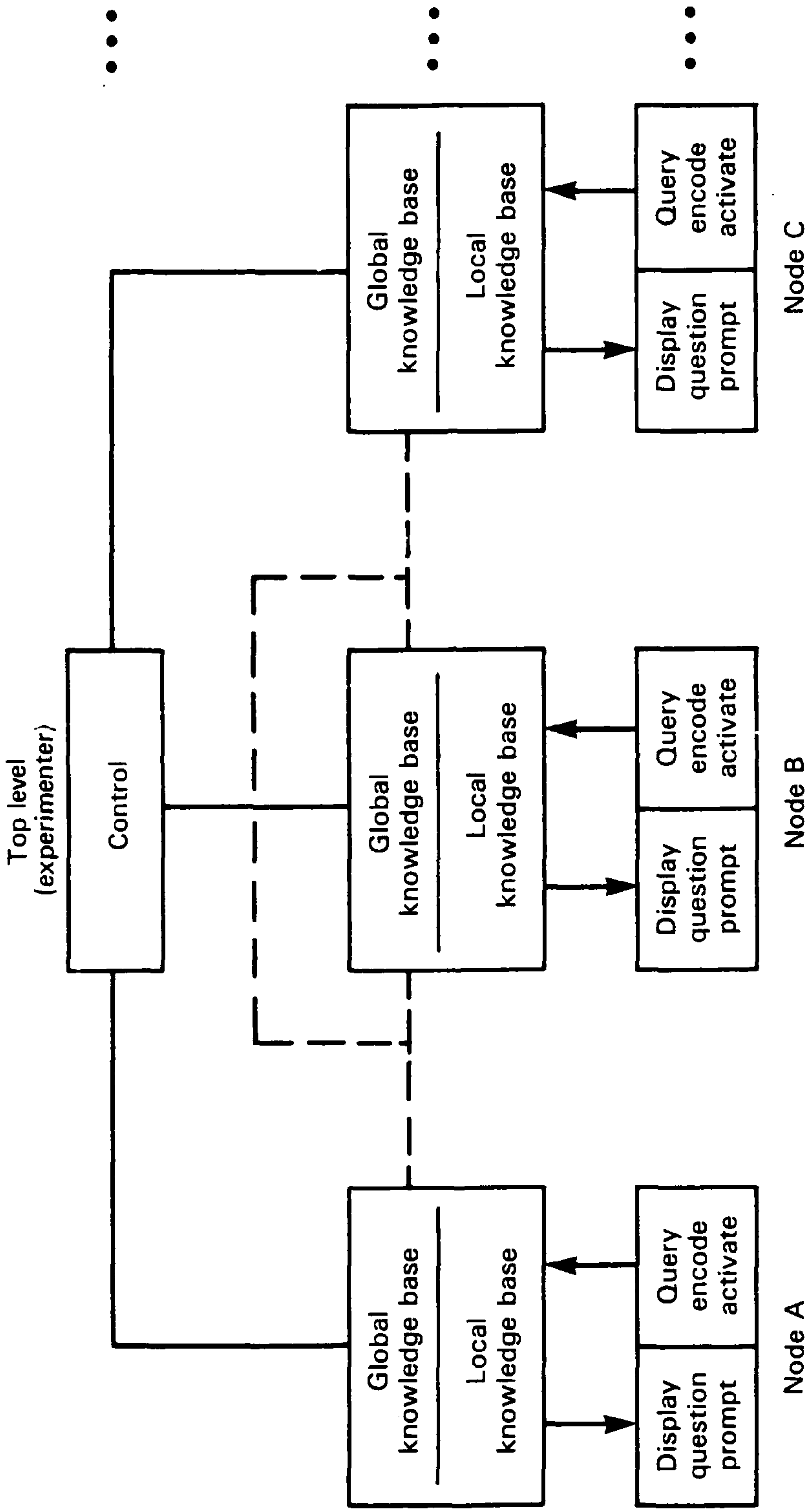

Figure 2. Experimental interview environment.

designed to stress plans and may affect two or more nodes of the distributed system. The three coordination states reflect conditions in which each decision maker (1) develops a plan optimized for his own mission requirements without coordination with his peers, (2) is shown the individually-developed plans of his peers to determine the nature of conflicts and synergies that appear, and (3) joins his peers in a negotiation meeting to discuss features of their individual plans in an effort to arrive at a mutually satisfactory plan that they can implement jointly.

The knowledge acquisition products were encoded, as possible, in computer programs and files in the experimental interview system. The elements of each plan were encoded in a structured format, which permits comparison of plan features across subjects for a given set of mission requirements. Agent definitions, when available, were arrived at through discussion with subjects, being encoded by the experimenters and checked for accuracy of intent and function by the subjects for whom they were defined. Knowledge states reflected in subjects' protocols were determined by the experimenters through analyses of interview documentation (notes, written products of the planning process, tape recordings, etc.) and in-process checks with subjects.

The initial conditions for the tactical scenario, as might be provided by the Officer in Tactical Command (OTC), or Composite Warfare Commander (CWC), of a battle group, were specified alike for each subject, and included information regarding

1. Concept of operations - specification of task group missions and rules of engagement,
2. Command/control organization - specification of composite warfare area commanders, their locations, and units assigned,

3. Available resources - identification of platforms, sensors, and weapons ready for use,
4. Intelligence estimate - specification of known and projected events and environmental conditions,
5. Enemy Order of Battle - identification of expected threats and tactics of the adversary, and
6. Schedule of events - chronological listing of actions required by OTC.

The definition of mission requirements was achieved in this environment through the specification of top-level goals to be attained by the group (as determined from validated scenarios). This specification was made by the experimenters in order to control the scope and structure of problems posed for subjects to solve. These top-level goals served as the basis for plan development by the subjects in the exercise of the functions of the three peer-level warfare area commanders.

A detailed description of the scenario and the initial information that served as the basis for planning by the subjects is provided in Stewart and Hamill (1987).

In our analyses, we attempted to represent the knowledge used by our teams of tactically experienced subjects in a structured framework, as indicated above, which permitted us to look at the products of the interview process in an organized way. Our focus was on decision maker interactions in the team negotiation session which followed the preparation of an individual plan by each team member, with the goal of building an explanatory qualitative model of the performance of these experienced subjects in a realistic tactical planning and decision-making task. Specifics of these analyses are contained in Stewart and Hamill (1987); results are summarized here in terms of features of subjects'

plans, discourse among subjects leading to development of a joint plan, and computer modeling and representation of individual and joint planning processes.

Analyses of platform dispositions. The plans of individual subjects, which were all based on the same previously learned structure for mission planning in the domain of Naval tactics, differed from one another in detail on the basis of warfare area assignment, specific goals, and specific knowledge about platform capabilities. These differences are illustrated in analyses of platform dispositions, that is, placement of available ships, aircraft, and submarines, each with its own prescribed sensor, weapon, and other operating capabilities, in geographical space in anticipation of mission-related events.

Several analyses of inter-platform distances, normalized to a common axis of advance, were conducted in search of relationships which might be expected among different groupings of the platform dispositions. There were nine platforms in the tactical problem: five surface platforms, two submarines, and two surveillance aircraft.

One set of analyses compared the inter-platform distances among the five surface platforms prepared by the five individuals within each of the warfare area commander roles and by the five teams in the joint negotiation sessions. There were only a few significant correlations found in the analyses in this set, indicating that there were almost as many different dispositions of surface ships as there were subjects within roles, or teams.

Adding submarine and/or air surveillance platforms to these analyses increased the number of significant correlations. For example, with seven platforms considered, the inter-platform distances for all five ASWCs were significantly correlated; with eight platforms, those for four of the five ASUWCs were significantly correlated; and with nine platforms, the inter-platform distances for the five team dispositions were significantly correlated. However, these

results must be considered in light of the much greater distances involved with submarine and air surveillance platforms as compared with surface platforms; the effect of these greater distances may be to suggest stronger relationships than are actually present.

Another set of analyses of the inter-platform distances for the five surface platforms compared the dispositions of the three subjects in each team and their jointly negotiated combined disposition. For Team 1, those for AAWC, ASUWC, and combined were significantly correlated; for Team 4, those for ASUWC and combined were significantly correlated; no other significant intra-team effects obtained, although additional significant correlations arose with the addition of platforms, as described above, in Teams 2, 3, and 4.

These analyses reveal few patterns where they might be expected to occur, as among subjects serving in the same warfare area commander role, or between individual subjects' dispositions and their own team's disposition, although there was some evidence of the latter for two of the five teams. This suggests that there are alternative acceptable solutions to the tactical problems being addressed. Further research with larger numbers of subjects and additional tactical problems would shed more light on these issues.

Analyses of team interview protocols. In order to understand the substance of the joint negotiation sessions conducted with the five teams, we analyzed the transcripts of those tape-recorded interview sessions. Two analyses were conducted.

In the first analysis, the five transcripts were coded for categories of information talked about by each speaker on each occasion on which he spoke. Nine categories were used: seven reflect knowledge and beliefs about the tactical problem being addressed; the other two indicate questions asked in search of some kind of problem-specific information, and other, often irrelevant, statements made during the course of the session. The nine categories were: communication requirements; platform disposition/formation; goal-related statements;

information requirements; knowledge about own forces; knowledge about threat forces; coordination requirements; questions asked; and other comments.

An analysis of variance performed on the tabulation of category frequencies showed no significant effect of warfare area roles, but significant effects of the above categories of information and of the interaction between roles and categories. The effect of categories was that discussion centered on knowledge about own forces, with relatively little attention given to requirements for communication, information, or coordination (although it should be noted that subjects were engaged de facto in a coordination effort).

The interaction effect between roles and categories indicated that knowledge about own forces, including detailed knowledge of sensor, weapon, and communication systems, tactics, equipment capabilities, and other situationally relevant specific information, played an important role in the negotiation discussions. Further, the ascendancy of the ASUWCs and ASWCs in this area attested to the teams' identification of the tactical problem as one emphasizing ASUW requirements, with important roles also played by submarines in both ASUW and ASW areas.

This analysis suggested the critical role played by detailed knowledge about factors relevant to the particulars of a tactical situation. It did not, however, capture other elements of the planning process which were observed during the negotiation sessions.

The second analysis was designed to get more directly at this planning process. For this analysis, the negotiation session transcripts (up to the point of agreement on a concept of operations) were coded for seven higher-level categories of discourse concerning: joint plan elements; conflicts in planning or knowledge; individual goals and plans; knowledge-oriented queries; assertions of knowledge; meta-planning issues; and social interactions.

Two teams of subjects had previously had experience in Naval tactics at the rank of Captain, while two other teams had had such experience at the lower rank of Commander. This analysis explored differences in the seven discourse analysis categories between these two sets of teams.

The Captains and the Commanders spent comparable proportions of their discourse events on assertions of knowledge (which accounted for the highest proportion of events at around 30%), knowledge-oriented queries (around 5%), and social interactions (under 5%).

Interesting differences appear, however, in the other four categories. The Captains spent about 25% of discourse events on joint plan elements and about half of that on individual goals and plans, while for the Commanders this distribution was approximately reversed, that is, the Commanders spent twice as much time asserting individual plan elements as they did asserting joint plan elements. Also, the Captains spent twice as many discourse events (over 15%) on meta-planning issues as did the Commanders, and only half as many (about 5%) as the Commanders on conflicts in planning and knowledge. This analysis points to four areas of planning activity in which qualitative differences may exist at different levels of Naval tactical experience.

One of the teams of Captains required only 35 discourse events to arrive at an agreed concept of operations. Reanalysis of just the first 35 discourse events for the four teams resulted in essentially the same relative distribution of discourse event categories as described above, suggesting that the differential emphasis on certain categories of discourse by more and less experienced decision makers is quite constant.

Schema-based representations. A system of schema-based representations for DTDM planning was developed on the basis of (a) Wilensky's (1983) process model for individual planning, (b) observed knowledge structures and processes, and (c) observed reasoning behaviors.

Wilensky's process model. The knowledge elements in Wilensky's planning model (the world model, goal statements, and plan elements such as a disposition diagram) may be combined with his processing elements (interpret situation, detect goals, propose/test/add plan elements, and execute and monitor) within a unified structure or schema system appropriate to the problem domain. Schemas are contextual data structures which represent knowledge about concepts, including objects, situations, events, actions, and sequences of actions. Using this concept of schemas we categorized Wilensky's model into declarative and procedural knowledge structures within the context of joint planning situations unique to battle group planning. These structures guided our experimental design (e.g., the world model provided to our subjects was developed in terms of standard Navy threat, intelligence, and resource documents), and they were subsequently modified to reflect observed behaviors better. Our objective, which was partially realized, was to derive empirically valid knowledge structures to extend and elaborate Wilensky's model to a DTDM context.

Observed knowledge structures and processes. Analyses of both individual planning artifacts and team negotiation session records indicated that subjects employed certain kinds of information structures and planning processes for organizing information about the tactical problem and its requirements, and for organizing their own knowledge for use in solving the problem. Limited representational formalisms for a computer model, such as production rule systems, were observed but were found not to be adequate for representing the diversity of observed structures and processes involved in tactical planning performance. The more flexible schema-based system was found necessary for representing those structures and processes, including: inheritance structures, supporting aggregation of lower-level planning objects, events, and structures, and permitting

the cascading of changes occurring through higher-level modifications of the current plan and its representation (e.g., "I thought that by having ships close together we could use flashing light communications"); default values for objects and procedures, not all of which would typically be specified by any individual decision maker, but all of which would possibly be needed at some stage of the planning process or in the course of implementation and monitoring of planned actions (e.g., "In the DDG51, they are in vertical launchers"); and expected values for objects and events related to the plans of own-force decision-making peers and opposition-force decision makers (e.g., "I assume M will move to fill the gap,...that's SOP").

Inheritance structures permit values at different nodes in the schema system to be used at other related nodes without requiring the values to be explicitly specified at all nodes where they may be needed. Default values permit plan features to be used even when those features have not been specifically identified in the immediate planning process, although such values need to have been set at some earlier time. These default values also permit decision makers to call upon standard operating procedures (SOPs) in the course of planning. The use of expected values permits decision makers to plan their actions in part in anticipation of likely actions of (a) friendly forces with which their actions must be coordinated (including presail agreements and SOPs) and (b) opposition forces.

Observed reasoning behaviors. Two types of reasoning appeared to predominate in subjects' planning behavior: rule-based reasoning and scene-based reasoning. The schema system was designed in part to support representation and analysis of such reasoning.

Rule-based reasoning employed production (situation/action, or if/then) rules to handle a number of planning activities, including: classification and ordering of facts related to the tactical mission; development of plausible facts, including use of defaults; definition of events on the basis of interrelated facts; derivation of expectations concerning facts and events; and derivation of actions or reactions to expected and actual mission-related events.

Corresponding examples of rule-based reasoning observed in interactions among subjects include

<u>Ordering facts</u>: "If my job is to prevent targeting...then my first concern is detecting him, and then..."

<u>Development of facts</u>: "If he lost power, he also lost radar."

<u>Derivation of expectations</u>: "If Red can't get a fix on us, I expect him to..."

<u>Derivation of actions</u>: "If we are pinging with sonar, then we should also..."

Scene-based reasoning employed complex sets of information and knowledge to manage the complexities inherent in realistic tactical problems involving multiple platform capabilities and their interrelationships, together with the myriad possible events in a tactical mission and their interrelationships. This scene-based reasoning was observed in subjects' definition of scenes (interrelating events, expectations, and associated actions or reactions); derivation of expectations from hypothetical and actual scenes; and determination of events leading to scenes, together with direct acquisition or association of possible actions or reactions.

Corresponding examples of observed scene-based reasoning include

Definition of scenes: "To retain mutual AAW support while using those towed arrays we should put them on our flanks."

Derivation of expectations: "In this situation I expect him to use his sub for forward search."

Acquisition of solutions: "In that case we should use the LAMPS helos for surveillance."

Although no rigorous distinction between rule-based and scene-based reasoning was discerned, problem statements and discourse associated with individual planning elements were generally rule-based, while the situation and action assessments associated with joint planning elements were generally scene-based. Thus, in terms of the discourse analysis associated with joint development of a concept of operations, all teams of subjects evidenced both forms of reasoning with the Commanders emphasizing rule-based reasoning and the Captains emphasizing scene-based reasoning. This suggests that a consequence of increased experience is decreased use of rules to generate plans and increased use of scene-matching to extract plans.

Command schema system. A computer model was developed in a schema-based framework to represent the principal components of the above warfare area commander knowledge structures, processes, and reasoning behaviors. The model took the form of a system of schemas, with individual schema types and their linkages defined in terms of observed categories of planning requirements. The command schema system is depicted in Figure 3. Prior to instantiation by an individual commander, each subschema consists of a collection of internal and inherited data variables and a set of methods or procedures associated with those variables. In the figure data structures and values are represented by ellipses, and procedures by rectangles (thus a computer-based schema is graphically depicted as a combination of an ellipse and a rectangle). Instantiation of the

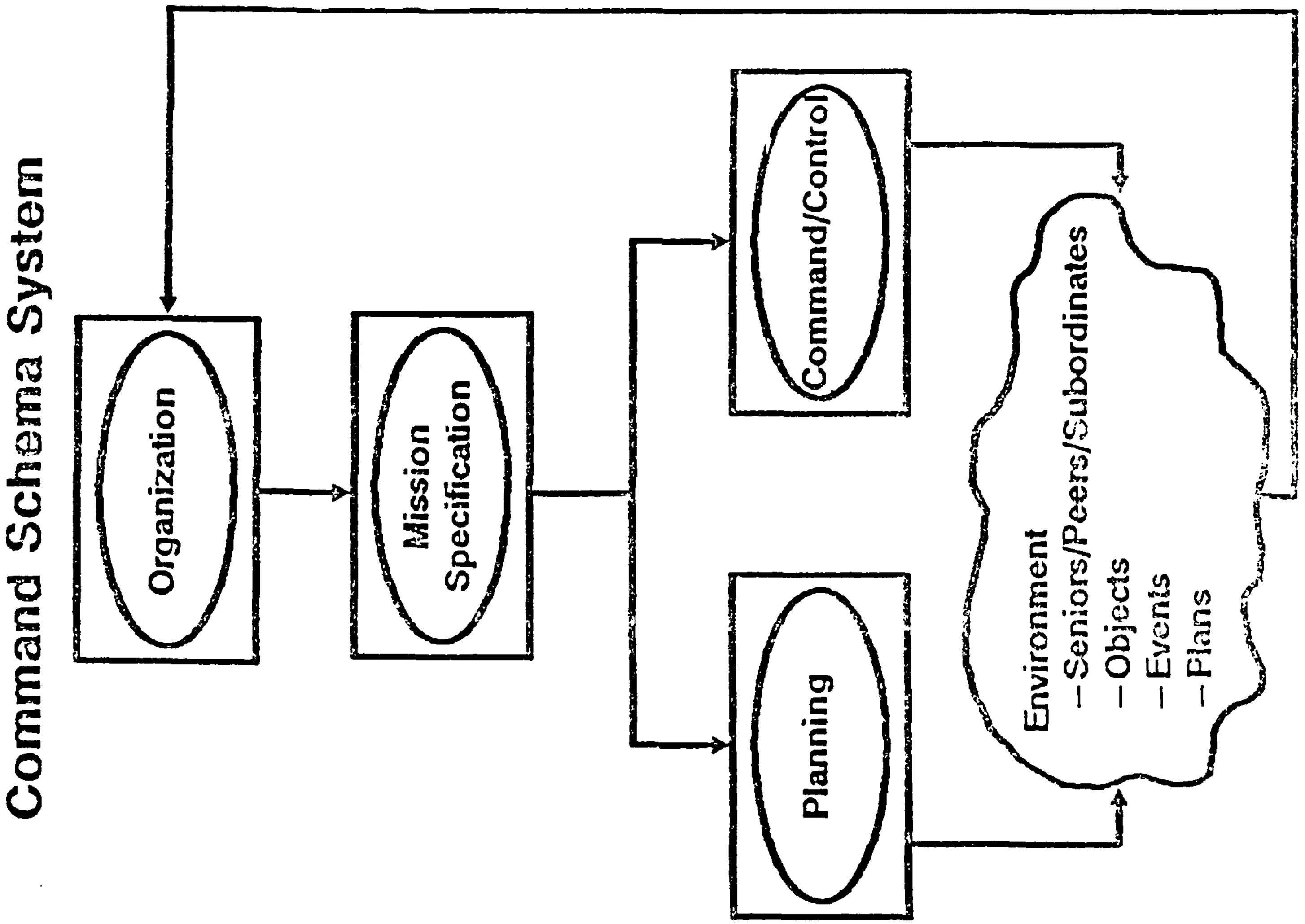
Command Schema System
Organization
Mission Specification
Command/Control
Planning
Environment
—Seniors/Peers/Subordinates
—Objects
—Events
—Plans

Figure 3

schema system by a human decision maker is emulated in the computer by loading the subschema structures, and executing associated procedures (e.g., rules) to read initial conditions, assert default values when initial data is incomplete, extend initial data, and initiate an internal agenda and agenda-maintenance method for controlling continued activity. Each subschema represents structure and, when instantiated, substance relevant to the aspect of command which it is intended to manage, together with pointers to other subschemas to which it is related or which it inherits when it is instantiated.

The Organization subschema thus represents variables and methods, including default values, production rules, declarative information, etc., which are needed to define such organizational functions as chain of command, assignment of warfare area commanders to platforms, staff assignments, and establishment and maintenance of the command-level mission agenda. Similarly, the Mission subschema represents mission-related variables and methods for generating top-level planning requirements and measures of Control effectiveness. The remaining command subschemas contain appropriate representations of variables, methods, and pointers for Planning and Control.

The environment is also represented as schemas, one which defines objects and events related to resources, readiness, the physical environment, tactical plots, engagements, and incidents, and another representing the several individually-developed plans and the joint plan developed by the team. (One common schema structure for a 'plan' is instantiated separately for each plan). Inheritance linkages ensure that a combination of schemas can produce all the data and procedures necessary to deal with the tactical problem being addressed by the system. Thus, the planning subschema inherits all of the data and procedures for mission specification and organization.

Using an extended form of the LISP computer language, the Command Schema

System was coded and exercised with observed subject data and methods on VAX and SUN computers. Validation of the computer model for the Planning subschema was initiated, with some success achieved in representing default reasoning and individual rules of the subjects. Comprehensive validation was not possible within limits of program resources and availability of subject data. It is clear from our preliminary efforts, however, that objective validation of schema-based decision models should be both feasible and valuable in further DTDM research.

Process model of distributed planning and decision making. Figures 4 and 5 show modifications and extensions of the individual planning process model shown in Figure 1 that reflect subject behaviors in terms of data structures and methods within a planning subschema.

Figure 4 depicts a planning process model for developing a joint plan which takes into consideration the perspectives, goals, and requirements of all three warfare area commanders (AAWC, ASWC, and ASUWC). The model is a representation of the observed process employed by subjects, including the continuing update of individual plans developed earlier to optimize the use of available resources for each subject's own mission requirements (a step which was imposed on subjects and might not formally occur in normal practice). The model reflects the several factors involved in establishing goal priorities for the joint plan and the various complexities that require consideration in coordinated planning by multiple decision makers.

In this model of joint planning activity, each of the three warfare area commanders brings to the negotiation an initial representation of the environment, his own world model of his warfare area, a model of the composite warfare approach (assumed uniform in our work), and a set of constraints, expected conflicts with other warfare areas, supporting rationale, and critical

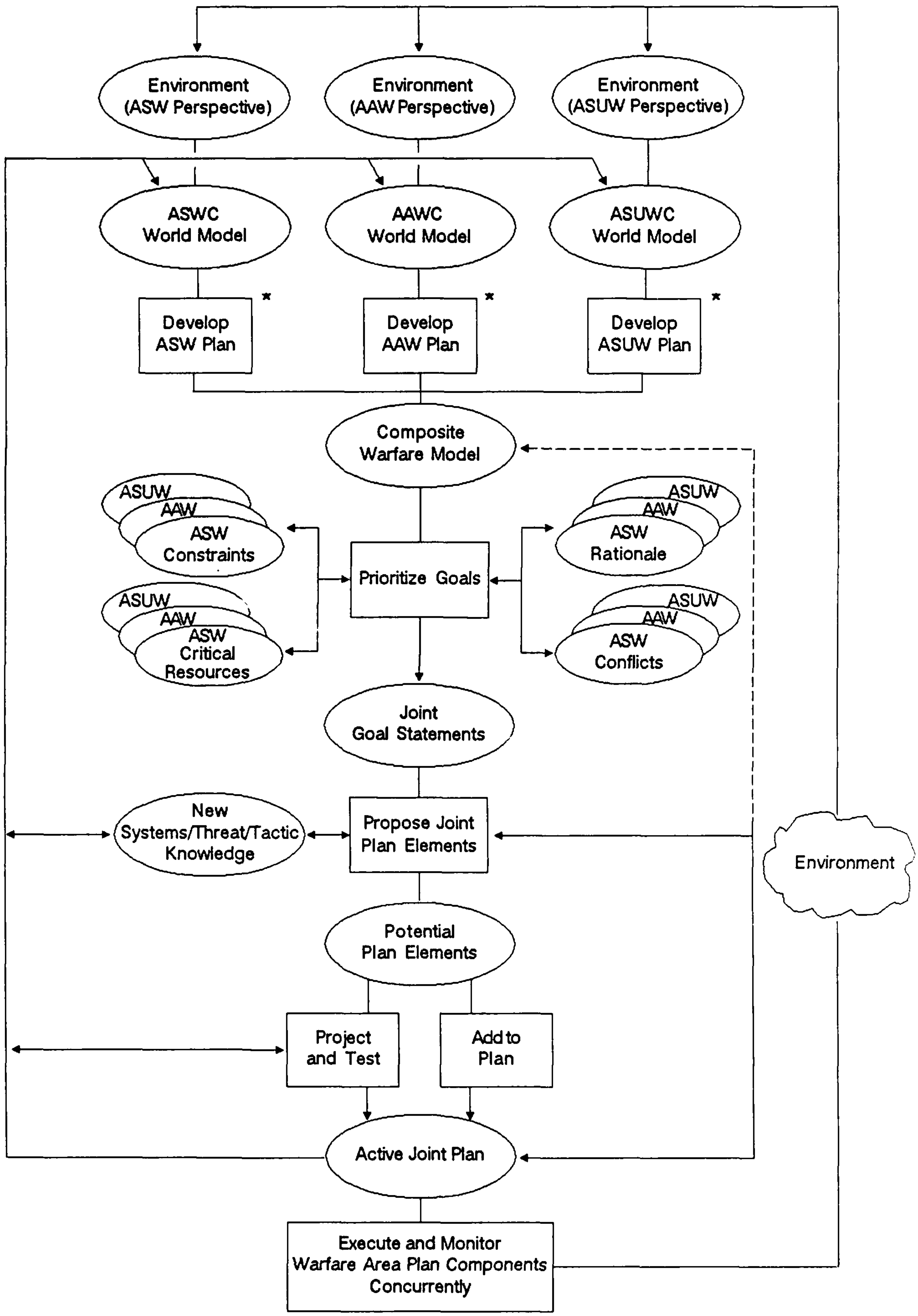

Figure 4. Planning process leading to joint plan.

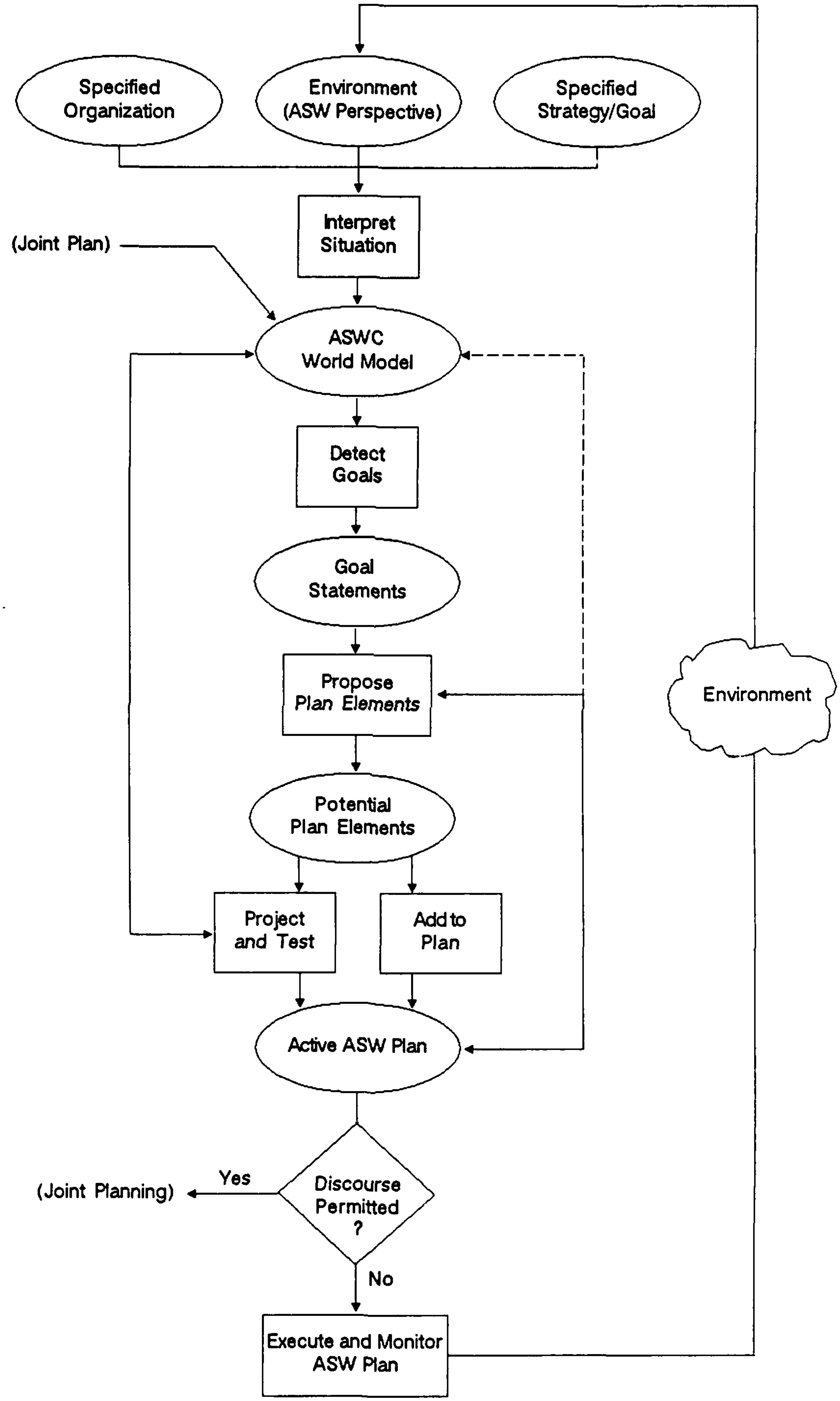

Figure 5. Ongoing planning process with joint plan implemented.

resources associated with achieving his goals. No common starting place within the model was discerned, but as subjects interacted to progressively identify and refine joint goals, and formulate related planning elements to be tested and added or rejected, a recurring sequence as depicted in Figure 4 was observed. As collective knowledge of the data and methods being used to prioritize goals increased, convergence to a single plan was observed in all teams but Team 3, where an unresolved conflict in belief regarding ASW capabilities precluded consensus on positioning of U. S. submarines in the scenario.

Figure 5 shows the ongoing planning process model with the joint plan implemented. In contrast with the individual planning process model of Figure 1, this model supports each of several decision makers (for example, the ASWC) operating separately but coordinating their actions with each other, even when they are not permitted to communicate. Each operates in accordance with elements of a joint plan in meeting his mission requirements, recognizing that each of the others has his own perspective and mission requirements, but also understanding their mutual commitment to specifics, as well as generalities, of the jointly agreed-upon plan. In the absence of communication, the joint plan is consulted for necessary guidance in dealing with unusual or unexpected situations; if communication is permitted, such situations can be discussed with the other decision makers, possibly resulting in replanning or alterations to the current joint plan.

Other Research Products

In addition to the project reports and analyses described, this effort produced: audio tape recordings and transcriptions thereof for each of the five team negotiation sessions; documentation of individual plans developed by all subjects; partial representations of all individual plans in a structured

computer-based format; and software for support of the experimental interview system described above. These products will be provided to the cognizant ONR Scientific Officer on request.

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